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Enhancing robustness of interdependent network by adding connectivity and dependence links

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HIGHLIGHTS

- Intra-degree, inter-degree and attack strength can affect how the attackers choose their attack mode.
- The attackers have the ability to choose the better attack mode in a very short time.
- We find a way to allocate the limited costs reasonably to get more robustness.

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ABSTRACT

Enhancing robustness of interdependent networks by adding connectivity links has been researched extensively, however, few of them are focusing on adding both connectivity and dependence links to enhance robustness. In this paper, we aim to study how to allocate the limited costs reasonably to add both connectivity and dependence links. Firstly, we divide the attackers into stubborn attackers and smart attackers according to whether would they change their attack modes with the changing of network structure; Then by simulations, link addition strategies are given separately according to different attackers, with which we can allocate the limited costs to add connectivity links and dependence links reasonably and achieve more robustness than only adding connectivity links or dependence links. The results show that compared to only adding connectivity links or dependence links, allocating the limited resources reasonably and adding both connectivity links and dependence links could bring more robustness to the interdependent networks.

1. Introduction

Network Science has attracted extensive attention since the small world model [1] and BA model [2] were proposed. Robustness, as one of the most important network properties, has attracted much attention. In the past decades, the robustness of individual network has been researched extensively [3–6]. However, many networks are not isolated but interdependent in the reality [7]. Especially with the development of information technology (IT), many critical infrastructures are coupled with internet and form the Cyber-Physical Systems (CPS). Several blackouts are the results of cascading failures between the cyber region and the physical region in smart grid, and different critical infrastructures are coupled together. The coupling of networks makes the individual model cannot apply to assessing the robustness of many interdependent networks, so many interdependent networks models are proposed to describe actual interdependent systems precisely [8–14].

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Gao, Buldyrev, Stanley et al. have done much research about the robustness of interdependent network [15]. In 2010, they came up with a cascading model of interdependent network which was called as one-to-one dependence model [16]. In this model, each node depends on no more than one node in the other network, and it was found that the interdependent networks are more vulnerable than isolated networks. The targeted attack on interdependent network under one-to-one dependence model was also researched [17]. In real world, one node may depend on more than one node, so multiple-dependence model [14] was proposed to correct the shortcoming of one-to-one dependence model. Besides, intersimilarity, as an important parameter, was introduced to measure the robustness of interdependent networks, and it was found that more intersimilarity means more robustness [18].

Enhancing the robustness of interdependent network is an important research field. A number of different enhancing methods have been proposed, including protecting the critical nodes, adjusting the properties of nodes, changing coupling preference and adding links. Protecting the critical nodes can apply to an existing network, but it is very difficult to identify the critical nodes. There is research showing that the identification problem is NP-hard [19]. Researchers usually take the node of high degree or heavy load as critical node, and Ruijin Du et al. [20] show we should protect the nodes whose sum of intra-degree and inter-degree are high. Besides, protecting the critical nodes cannot make sure the protected nodes will not be captured, and some research shows that it is difficult to defend the interdependent system by protecting the high-degree nodes [21]. Adjusting the properties of nodes is another way, and in load-induced interdependent network, it manifests as adding the node's capacity [12,13,22]. In Parshani's model [8], it manifests as making a node autonomous. The disadvantages of adjusting properties of nodes are, it is expensive compared to adding links, and in normal state (when the interdependent network is not being attacked), the extra capacity cannot enhance the system's function. Changing coupling preference is also a useful way and takes low costs. Meng Tian et al. [23] showed that we could enhance the robustness by increasing inter-community connections against random attacks and targeted attacks. Another research [24] also done by this research group aims to enhancing the robustness by inter-similarity link patterns. However, changing coupling preference can only apply to designing networks. Adding links takes low costs and is easy to operate on existing networks, so it is an appropriate solution to enhance the robustness of interdependent networks.

Many link addition strategies [25–29] have been proposed both in individual networks and interdependent networks. Xingpei Ji et al. [29] discussed how to enhance the robustness of interdependent network by only adding connectivity links based on Ref. [18], and they proposed low inter degree-degree difference based addition strategy and random inter degree-degree difference based addition strategy. Correspondingly, based on the results of Refs. [23] and [24], the strategy of adding dependence links can be gotten, and it is that we should manage increasing the inter-community connections or use inter-similarity-link patterns when we add the dependence links. However, with so much research above, there are still some problems to be solved. Firstly, most of researchers test the effects of adding links under random removal, but in the reality, failures may be the results of targeted attacks. Before the defenders choose the link addition strategies, they must understand what threats they would meet, because different attack modes bring different attack effects and need different link addition strategies. Secondly, the link addition strategies at present are all only adding connectivity links or only adding dependence links, what if we add both kinds of links with the same costs, could we get a more robust interdependent network? If we can, in the condition that the costs of adding a connectivity link and adding a dependence link are different. How to allocate the limited costs to add connectivity links and dependence links reasonably should be researched.

In this paper, two attack modes are considered. One is intra-degree priority mode and the other is inter-degree priority mode. The attackers are divided into two kinds, stubborn attackers and smart attackers. The stubborn attackers always choose the same mode no matter what structure of the network has. The smart attackers choose the mode that brings more damage based on the structure of the network, and when the network structure is changed, the smart attackers may change their attack modes accordingly. Our results imply that there is a way for the attackers to choose the attack mode that brings more damage once they get the structure of the interdependent network. So when we design the link addition strategy, the situation of smart attackers must be considered. The link addition strategies are given to reduce the attack effects for different kinds of attackers, and the defenders can get an optimal link addition strategy with which they could enhance the robustness of interdependent networks most. The optimal link addition strategy we get shows that allocating limited costs for adding connectivity links and dependence links reasonably is better than simply adding connectivity links with all resources. The conclusions enlighten the research of enhancing the robustness of interdependent networks by adding links, and they imply that the costs allocation scheme is also very important.

The paper is organized as follows: the failure model of interdependent network, two targeted attack modes and problem definition are introduced in Section 2. Link addition strategies are given under different attackers in Section 3. In Section 4, we discuss whether the link addition strategy can apply to coupling BA networks and how the defenders do when they do not have knowledge of the attackers' attack mode. At the end of the paper, the conclusions of this paper are made.

2. The model

In this section, we review the multiple-dependence model and measurement of the robustness of the networks under attack. Then, two attack modes, namely intra-degree priority mode and inter-degree priority mode are introduced. At last, the definition of the link addition problem we aim to solve is given.